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16. Abstract

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SUMMARY

A new, remotely augmented vehicle concept for flight testing advanced control systems has been developed at the NASA Flight Research Center as an outgrowth of a remotely piloted research vehicle program. The control laws are implemented through telemetry uplink and downlink data channels and a general-purpose ground based digital computer which provides the control law computations. Some advantages of this approach are that the cost of one control system facility is spread over a number of RPV programs, and control laws can be changed quickly as required without changing the flight hardware. This paper describes the remotely augmented vehicle concept, discusses flight-test results from a subscale F-15 program, suggests how the concept could lead to more effective testing of RPV control system concepts, and suggests an application to a military RPV reconnaissance mission.

INTRODUCTION

The ever-widening role that remotely piloted vehicles are being asked to play in military applications as well as in flight research demands a corresponding increase in the capability of their flight control systems. This increased capability is usually achieved through greater sophistication, but at the expense of increased complexity. Designing and optimizing one of these sophisticated systems for its intended mission is constantly becoming more difficult. This paper suggests a cost effective method — the remotely augmented vehicle (RAV) method — that makes it possible to substantially modify or refine the design even during the flight-test phase. The method involves implementing the control system on a ground based computer, then utilizing RPV telemetry uplink and downlink data channels to close the control loop around the airplane.

The NASA Flight Research Center has gained experience with the RAV concept by applying it to two airplanes. The first was a piloted, twin-engined airplane which was used to develop the concept (ref. 1). The second was a remotely piloted scale model of the F-15 airplane. The RAV concept, the scale model F-15, and the remote augmentation ground facility are described briefly in this paper; more detailed descriptions are presented in reference 2. This paper also suggests possible applications of the RAV concept to RPV military missions.

SYMBOLS

$a_i, b_i, c_i, d_i, \alpha_i, \beta_i$	coordinates of poles and zeros of general s-plane transfer function
C^*	longitudinal handling qualities index, $n_z - \frac{V_{co}}{57.3g} q$, g
$G(\cdot)$	general transfer function where $(\cdot)$ is (s) or (z)
g	acceleration due to gravity, m/sec^2
i	index variable in general transfer functions
$K_{(\cdot)}$	feedback gain associated with $(\cdot)$
K_s, K_z	general filter gain constants in s- and z-domain, respectively
k	index variable in general z-plane transfer function
n, t	number of complex pairs of roots in numerator and denominator, respectively, of general transfer function
n_y, n_z	lateral and normal accelerations, respectively, g
p, q, r	body axis roll, pitch, and yaw angular rates, respectively, deg/sec
r_s	stability axis yaw rate, deg/sec
s	s-plane complex variable
T	sample period, sec
u	input to generalized first-order low-pass filter
u, r	number of real roots in numerator and denominator, respectively, of general transfer function
V_{co}	crossover velocity, m/sec
w	w-plane complex variable, $\frac{z - 1}{z + 1}$
x	output of generalized first-order low-pass filter
z	z-plane complex variable, e^{sT}

β	pole location of first-order low-pass filter
$\delta_1, \delta_2, \delta_3, \delta_4$	general uplink commands of remotely augmented vehicle system, deg

Subscripts:

k, k-1	current and previous sample points, respectively

REMOTELY AUGMENTED VEHICLE CONCEPT

The remotely augmented vehicle concept is illustrated in figure 1. Airplane motion is sensed on board the airplane and transmitted to the ground by means of a telemetry downlink. Signals representing the motion variables are sent to the digital computer, which contains programed control laws. These control laws, which represent a control augmentation system, generate control signals based on the motion variables and the pilot's inputs from the ground cockpit. These signals are then transmitted to the airplane through a telemetry uplink and converted into control surface motions on board the airplane.

Ground Based Computer

The key to the RAV concept is the use of a versatile ground based general-purpose computer. Either an analog or a digital computer could be used, although the digital approach has several advantages. The main objective is to mechanize (or simulate) as much as possible of the proposed flight control system on the ground computer. Use of the computer makes it possible to quickly change the characteristics of the test system as the need arises during development and flight test without changing the flight hardware.

Use of a digital rather than an analog computer has the primary advantage of making the implementation and modification of logic functions straightforward. Flexibility in the logic implementation is particularly important, in that the more sophisticated control systems usually require a large amount of logic operations. An additional benefit of the digital approach is the repeatability it provides, which is important in troubleshooting developmental problems and in verifying correct operation. Precise inputs, such as controller commands duplicated from previous maneuvers, may be inserted by using the digital computer as a storage device, commanded indirectly through a switch at the ground cockpit.

Other advantages of a digital computer over an analog computer depend on the particular application. If the control system mechanized on the ground based computer is intended for eventual onboard implementation, it can be thought of as a simulation of the onboard system. If the system being simulated is digital, then of course a digital remote augmentation system is superior. But, if the system being simulated is analog, an analog remote augmentation system is not necessarily the most desirable. A straightforward procedure for simulating an analog system with a flexible digital system is presented in the appendix. If the telemetry links for the

RPV are digital, no additional analog-to-digital and digital-to-analog converters are necessary for the RAV system. Considering all these factors, a digital remote augmentation system usually provides the most efficient means of simulating an operational analog system.

Use of RPV Telemetry Links

In an RAV system, downlink and uplink telemetry systems are required to close the control loop around the RPV through the ground based computer. In any flight-test program, it is common for a downlink telemetry system to fullfill the normal data acquisition requirements. The parameters recorded are usually more than sufficient to provide the response variables necessary for most flight control systems. Only an interface with the ground computer is necessary to complete the downlink portion of the RAV system.

Uplink telemetry is also a normal part of any RPV system, although it may be inadequate to meet the data rate requirements of an RAV system. General data rate requirements are not easily specified, since they are a function of the number of controllers being commanded, the number of bits per word, and the sample rate, which can be different for each controller. Sample rates do not have to be much higher than twice the frequency of interest for correct simulation of the dynamics; however, sample rates this low may cause unacceptable quantization in the controller response. The individual application must be examined on a case-by-case basis to determine if the uplink system being used for RPV control is adequate for an RAV system as well.

Transition From Simulation to Flight Test

In preparing for any flight test, whether of a remotely augmented vehicle or a conventional aircraft, a large amount of simulation is required. This involves simulation of the vehicle's aerodynamics as well as the control system and should be distinguished from the type of simulation discussed previously in which the RAV system simulates the onboard control system.

One advantage of the RAV concept is that the transition from simulation to flight test can be made in such a way that the control system is essentially identical in both instances. The most obvious example is when the computer that is used for simulation development is also used as the ground computer in the RAV system. In some applications it may be advantageous to use a large general-purpose computer for the simulation, taking advantage of its debugging and programing aids, and a minicomputer for the flight-test mechanization. If care is taken in programing the large computer, the same program card deck may be used as the input to both computers. The ability to verify a program through extensive simulation and then use the same program for flight test increases the confidence in the test results.

REMOTE AUGMENTATION SYSTEM GROUND FACILITY

Once the NASA Flight Research Center's remote augmentation system ground facility was developed, it was available for use with many different vehicles; thus, the cost of the facility was spread over several projects. The ground facility telemetry data links and interfaces, the computer, and the overall timing and synchronization of these components are described in this section.

Telemetry Data Links and Interface

Telemetry downlink.— The NASA Flight Research Center's telemetry flight data acquisition system is used as the telemetry downlink portion of the RAV system. This pulse code modulation (PCM) system provides each of the aircraft response variables to the ground station at 200 samples per second. The characteristics of the system are as follows:

144,000 bits per second
9 bits per data word
80 PCM words per PCM frame
200 PCM frames per second
No parity check
L-band transmission
12-foot parabolic receiving antenna slaved to radar tracking antenna

The system has 40-hertz first-order-lag analog prefilters on all channels. The low power (5 watts) and the lack of parity check on the downlink make it advisable to perform software reasonability checks to discriminate against bad telemetry data.

Downlink telemetry data are transferred to the computer by a downlink interrupt servicing routine at 200 samples per second for each response variable. The values of the variables are represented by a 0 to 511 decimal count format in a continuously updated table of telemetry data.

Telemetry uplink.— The telemetry uplink used for the system was developed by the U.S. Navy for the remote control of drone aircraft. The system is capable of several modes of operation, from the control of a single drone to the time-multiplexed control of a fleet of drones. Because it can control more than one drone simultaneously, the update rate of the system when controlling a single aircraft is comfortably high. Consequently, the system is adequate for RAV operation. The characteristics of the system are as follows:

16 bits per data frame (10-bit proportional command signal and 6 discrete signals)
4 data frames per cycle
53.33 cycles per second
2 parity checks per data frame
Synchronization and parity checks on each cycle
UHF band transmission

Figure 2 illustrates the format of each cycle. The transfer of each data word from an uplink encoder to a receiver output on board the airplane requires 3.75 milliseconds.

Overall telemetry operation.— The time delay of the telemetry data links in the RAV system is approximately 3.3 microseconds per kilometer, which yields a total time delay of approximately 0.5 millisecond through the downlink and uplink channels when the test airplane is at a range of 75 kilometers. This is an acceptable time delay, compared to the total computational delay through the RAV system.

The number of bits in the downlink and uplink telemetry channels (9-bit downlink and 10-bit uplink) was chosen to permit valid implementation of typical closed-loop aircraft control laws. Simulator studies indicated that little increased performance was achieved with more than 10 bits, whereas less than 9 bits led to deterioration in performance, as evidenced by granularity in the command signals and a tendency to limit cycle.

Computer

The computer used in the RAV system is a general-purpose, rack-mounted minicomputer with a 24K memory consisting of 16-bit words and with a 750-nanosecond cycle time. The peripheral equipment includes a card reader, line printer, magnetic tape unit, disc unit, teletype, paper tape reader/punch, and peripheral floating point processor. The software is composed of an assembler, a FORTRAN compiler, an on-line debugging program, and a mathematical subroutine support library.

A computer program has been written which implements the control law computations by using floating point FORTRAN programing. Thus the FORTRAN compiler is used to debug and check out the program, and the floating point feature reduces the necessity of scaling the variables. The computer program also has assembly language subroutines which perform all input/output of data and which pass the data to and from the FORTRAN main program.

Timing and Synchronization

The input/output interface at the computer is illustrated in figure 3. The signal flow for data words between the ground cockpit, with a mode control and pulse panel, and the computer is shown as well as the telemetry interfaces. The number of bits in the data words passed to and from the computer is indicated in the arrows. Transmission of a set of data words is initiated in response to an interrupt into the computer.

Figure 4 shows the time sequence of operations of the RAV system. The FORTRAN program computation sequence is controlled by the uplink interrupt. For instance, during frame 1 the program computes the command signal, δ_1. This command signal is passed to the uplink interrupt servicing subroutine, and the FORTRAN program then waits in an idle loop for an uplink interrupt. When the interrupt occurs, the FORTRAN program determines if δ_1 was requested and, if so, begins computing the next command signal, δ_2. If any other command was requested, the FORTRAN program branches to the appropriate frame in an attempt to get back into synchronization.

During frame 5, the FORTRAN program accepts the cockpit data, determines the mode control panel status, and performs mode switching initialization, if necessary.

The downlink system is asynchronous with respect to the uplink system. The PCM data are provided at 200 samples per second, and the uplink commands are updated at 53.33 samples per second. The high data rate of the downlink system is used to minimize the time delay through the closed-loop system; all telemetry data are accepted but only the most recent value of a downlink variable is used. Thus the effective overall sample rate of the flight control system is that of the system with the lowest sample rate, in this instance, the uplink system.

The throughput delay associated with the computer and encoder varies from 7.5 milliseconds to 12.5 milliseconds. The minimum delay occurs when a sensed variable enters the computer immediately before the beginning of the frame in which it would be used. The variable would be used to update the command signal during that 3.75-millisecond frame and would be transmitted to the test airplane to update the airplane's controls at the end of the following 3.75-millisecond frame. The maximum delay of 12.5 milliseconds could occur if the sensed variable enters the computer immediately after the variable is used in the previous frame, that is, 5 milliseconds before the current computation frame begins.

As an example of the approximate total lag through the system, from sensor output to control surface actuator command, the following lag would be accumulated for a 5-hertz signal with a vehicle located 75 kilometers from the ground station:

	Time delay, milliseconds
40-hertz analog prefilter	4.44
Downlink (PCM) encoding	.06
Transmittal to ground station	.25
Average computer/encoder throughput	10.00
Zero-order hold	9.40
Transmittal to airplane	.25
Average total time delay	24.40

This time delay corresponds to a 44° phase lag at 5 hertz, an acceptable lag for most applications. If this lag is unacceptably large, some lead could be generated by programing a lead-lag filter in the digital computer.

SUBSCALE F-15 PROGRAM

The NASA Flight Research Center is flight testing a large-scale model of the F-15 airplane in an effort to correlate model and full-scale stall, departure, and spin controllability data. The remotely piloted method of flight test was selected because high-risk departure and spin tests could be made at lower cost and less risk than with a piloted vehicle. An important aspect of the program is the simulation of the F-15 airplane's control system using the RAV concept. As a result, the subscale F-15 program is an excellent example of the usefulness of the RAV concept.

F-15 Model

The F-15 model was constructed primarily of fiber glass, with metal load-carrying members in each section. The unpowered model was air-launched from a B-52 airplane. A photograph of the model in the launch position under the B-52 wing is shown in figure 5. Batteries powered all onboard systems, including the electrohydraulic actuators which positioned the control surfaces. The control surfaces consisted of stabilators, ailerons, and twin rudders. The control surface actuators had 10-hertz bandwidths. A detailed description of the model and instrumentation system is given in reference 2.

Description of Control Laws

The objectives of the subscale F-15 program relative to flight control systems were: (1) To implement basic control modes which provided good handling qualities at high angles of attack, and (2) to simulate the full-scale F-15 flight control systems for low-speed flight. To meet these objectives, two basic control modes and two simulated F-15 control modes were implemented in the computer. The four modes and their key features are summarized in the following table:

Function	Mode	Features
Basic	Computer direct	Nonlinear pitch gearing
	Rate damper	High gain rate feedback
Simulated F-15	Mechanical control system	Unaugmented primary system
	Control augmentation system	Full authority C^* command

Basic modes. — A block diagram of the basic modes is shown in figure 6. The solid lines represent the initial computer direct mode, and the dashed lines represent the additional feedbacks constituting the rate damper mode. The pilot's longitudinal stick displacement was modified by a nonlinear gearing schedule which commanded the stabilators collectively. The lateral stick commanded the ailerons directly and the rudders indirectly through an aileron-to-rudder interconnect. The interconnect gain was scheduled as a lagged function of pitch stick position. The rudder pedals controlled the rudders directly.

In the rate damper mode, damper commands were summed with the pilot's commands, whereas the computer direct mode used only the pilot's commands. The damper commands consisted of pitch rate, q, fed to the collective stabilators, roll rate, p, fed to the differential stabilators, and yaw rate, r, fed to the rudders. Each of the rate gyro signals was low-pass-filtered at 6 hertz and notch-filtered to eliminate the dominant structural resonances near 20 hertz. The feedback gains were as follows:

Quantity	Maximum rate damper gain
K_q, sec	0.4
K_p, sec	0.8
K_r, sec	4.0

Simulated F-15 modes.— Figure 7 is a simplified diagram of the F-15 flight control system as it was programed in the ground based computer. The F-15 mechanical control system (MCS) is shown by the solid lines. The dashed lines represent the additional control augmentation system (CAS) components. When in one of the simulated F-15 modes, the MCS operated at all times; therefore, the CAS mode consisted of the MCS plus the additional CAS components. Each control surface in the full-scale F-15 airplane is driven by a power actuator. The electrohydraulic actuators on board the F-15 model effectively simulated these full-scale power actuators, so they were not simulated in the ground computer program. The feedback gains were as follows:

Quantity	Simulated F-15 control augmentation system gain
K_{r_s}, sec	0.613
K_{C*}, deg/g	1.0
K_{n_y}, deg/g	9.2

Diagrams of the pitch and roll systems are shown in figure 7(a). Left and right stabilators are driven directly from the pilot's pitch and roll stick when the MCS is operating. The roll MCS stick-to-surface gearing on the roll stick is programed as a lagged function of pitch stick position in order to restrict differential stabilator deflection when the pitch stick is commanding large deflections of collective stabilator. In the pitch axis the addition of the CAS results in a blended normal acceleration and washed out pitch rate control augmentation system. This is a modified form of a signal commonly referred to as $C*$ (ref. 3). In the roll axis a simple feedback of roll rate is compared with commanded roll rate which is a function of roll stick force. A limiter on the roll CAS command to the differential stabilators was provided, with the limit values programed as a function of angle of attack.

Figure 7(b) is a diagram of the yaw system. When only the MCS was used, the rudder pedals were summed with an aileron-to-rudder interconnect to command rudder position. The addition of the yaw CAS provided stability axis yaw rate feedback, lateral acceleration feedback, and increased rudder pedal authority. Stability axis yaw rate was estimated by summing the measured body axis yaw rate with a correction term based on roll rate and angle of attack. Although not shown in figure 7, each of the sensed motion variables was notch-filtered in the computer at approximately 20 hertz. The algorithm described in the appendix was used to compute the digital filter coefficients.

Support Simulation

A complete simulation of the entire closed-loop system was developed, including the F-15 model aerodynamics and the RAV system components. The simulation was performed on the NASA Flight Research Center's central computer system, utilizing its real-time simulation capability. The airplane's continuous differential equations of motion were integrated numerically, using a modified second-order Runge-Kutta integration technique. Even though mechanized on a digital computer, this simulation of the F-15 model aerodynamics is referred to as the continuous F-15 simulation.

In order to evaluate the digital mechanization of the control system, two different simulations were used for the RAV control system. The first, called the digital RAV simulation, duplicated the difference equations as they were mechanized for the ground computer. The same card deck that was to be used for the ground computer FORTRAN program could be run directly on the central computer to provide verification of the program deck. These RAV control law equations were processed at 50 samples per second, and the resulting commands were used by the continuous F-15 simulation operating at 200 samples per second. The second method, called the continuous RAV simulation, mechanized the analog F-15 control laws. The modified Runge-Kutta integration technique used for the aerodynamics was also used to solve the differential equations. Computations were made at a high rate of 200 samples per second in order to give a good representation of the RAV analog equivalent.

A comparison of the results from these two simulations is shown in figure 8 for the pitch response to a pull-up maneuver. The pitch CAS mode was selected, and the pilot inputs were identical for both simulations. This comparison indicates the effectiveness of the digital system in duplicating an analog system.

FLIGHT RESULTS AND EXPERIENCE

High Gain Feedback Performance

The rate damper modes provided the highest feedback gains used in flight. The effectiveness of the pitch, roll, and yaw dampers is shown in figures 9 and 10. Figure 9 shows the open-loop pitch response to a pitch stick doublet followed by the operation of the pitch damper after several oscillations. The pitch damper was effective in damping the short-period mode of the vehicle; the response agreed closely with the simulation results and the analysis that preceded the flight tests.

Figure 10 shows the operation of the roll and yaw dampers at an angle of attack of approximately 30°. A damper-off maneuver is shown, followed by the engagement of the damper system. During the maneuver, the model is excited by electrical command pulses to the ailerons; these pulses are shown on the aileron trace as pulse panel inputs. The pilot did not use the rudder pedals; hence, all rudder motion was due to the aileron-to-rudder interconnect and the yaw damper. The figure shows that the Dutch roll mode of the open-loop airplane at this angle of attack was unstable for small oscillations and that the dampers were effective in damping the oscillations.

Operational Experience

The operation of the RAV system during the first nine flights of the subscale-model F-15 program showed that the RAV approach to flight testing is promising for developing new flight control systems. The RAV system, which utilized a ground based computer, did not experience a failure during flight; however, problems did occur with the telemetry downlink and uplink that affected other facets of the operation.

On one flight the ground station receiver was slightly out of adjustment, which made the remote pilot's displays unusable because of downlink dropout. No other downlink dropout was experienced during the test time on any of the other flights.

The uplink command system functioned perfectly on all but one occasion, when a faulty boresighting of the uplink system ground antenna caused inaccurate tracking of the model. The result was a low signal level and loss of control from the ground facility. The model was recovered by using the normal parachute recovery technique.

No dropout of the telemetry links was experienced as a result of extreme maneuvers. The F-15 model was flown through a wide range of attitude, including 360° rolls and 90° nose-down attitudes. High oscillatory rates of 200 deg/sec in roll, 100 deg/sec in pitch, and 200 deg/sec in yaw were sustained.

As an example of the flexibility available through the RAV approach, the computer direct mode was modified for the most recent flights so that the pilot's roll stick commanded the stabilators differentially rather than the ailerons. The ailerons were disabled and set to zero. The modification was made by a simple programing change in the ground computer FORTRAN program; no modifications to the model were required.

Comparison of Flight and Simulation Results

One of the advantages of the RAV technique is the easy transition from simulation to flight test. Good agreement was obtained between the simulation results and the flight-test data, thereby making it easy to investigate flight peculiarities on the simulator. An example of the good agreement is shown in figure 11, a comparison of the F-15 model's pitch CAS responses during flight and from the digital RAV simulation. No adjustments in the control system were made to obtain this match. Good correlation is shown in each of the motion variables. The pilot's input was the same as that in figure 8. The data storage capabilities of the NASA Flight Research

Center's central computer system make it possible to use identical inputs in order to compare results.

POTENTIAL APPLICATIONS

The use of the RAV concept in the subscale F-15 program not only provided a practical method of implementing a control system in a research program but also established the feasibility of using the RAV concept for a more general RPV application. Consequently, the practicality of adapting the RAV concept to specific military applications is worth considering. Two possible applications are suggested.

The first possibility involves developmental testing of RPV's. The use of a ground facility with computer and telemetry uplink and downlink channels would permit one set of control law hardware to be shared by a number of similar or dissimilar RPV's. The control and guidance laws could be totally reconfigured for the various RPV tests simply by reloading the computer. A number of candidate control and guidance concepts could be investigated with each RPV in the actual flight environment before deciding on the final flight hardware. During the period when changes in the control laws are usually required, the changes could be made quickly, using the ground based computer. No flight hardware would be affected. As the system configurations were finalized, operational versions of the control systems could be implemented on board the operational vehicle.

The second possibility involves an operational RPV in a military reconnaissance mission. Frequently, a manned support airplane is required in line-of-sight support of the RPV in order to relay television signals from a camera on board the RPV to a monitor used by the ground operator. The support airplane usually has a general-purpose digital computer on board. It may be possible to use this computer to remotely augment the RPV, rather than providing the entire control augmentation system on board the RPV. Possible advantages of using the RAV concept in this manner are the elimination of some electronics in the expendable RPV, the ability to implement more sophisticated and better performing control laws in the digital computer, and the ability to change control system equations in order to adapt to the specific mission constraints. In addition, the computer system in the support airplane could be used with a variety of RPV's by having different software packages for each type of RPV.

CONCLUDING REMARKS

A new, remotely augmented vehicle concept for testing advanced control systems using a ground based computer and uplink and downlink telemetry data channels has been successfully demonstrated as part of a remotely piloted scale-model F-15 program. Some advantages of this technique for RPV applications are as follows:

(1) A remotely augmented vehicle facility can be used for many different vehicles, thus spreading the cost of the facility over many projects.

(2) Control laws can be changed quickly as the need arises during development and flight test without changing the flight hardware.

(3) Repeatability is improved when a digital computer is used as the ground based computer. A digital mechanization can simulate the performance of an analog system if necessary.

(4) Progression from simulation to remotely augmented vehicle flight test is straightforward. Discrepancies can be isolated easily and system mechanization verified easily.

APPENDIX

DIGITAL SIMULATION OF ANALOG COMPONENTS

If a digital computer is selected as the ground based computer, the analog components that may be part of the proposed flight control system must be simulated. Several techniques are available for creating a discrete representation of continuous transfer functions. One technique which has been successfully demonstrated (ref. 1) illustrates the general approach to the problem. Basically, the technique transforms a continuous transfer function of general form, $G(s)$, into a discrete transfer function, $G(z)$, which can then be implemented on the digital computer as difference equations. An algorithm for making this transform can be derived which is equivalent to a two-step process: (1) conformal mapping of the continuous s-plane to the discrete frequency w-plane by means of the expression $w = \tanh \frac{sT}{2}$ followed by (2) the bilinear transformation from the w-plane to the z-plane by means of $z = \frac{1 + w}{1 - w}$. The resulting algorithm can be stated in the general form, given a continuous transfer function of the form

$$G(s) = \frac{K_s \prod_{i=1}^{u} (s + \alpha_i) \prod_{i=1}^{n} \left[(s + a_i)^2 + b_i^2 \right]}{\prod_{i=1}^{r} (s + \beta_i) \prod_{i=1}^{t} \left[(s + c_i)^2 + d_i^2 \right]}$$

A digital filter approximating $G(s)$ is given by

$$G(z) = \frac{K_z (z + 1)^k \prod_{i=1}^{u} \left(z - e^{-\alpha_i T} \right) \prod_{i=1}^{n} \left(z^2 - 2e^{-a_i T} \cos b_i T z + e^{-2a_i T} \right)}{\prod_{i=1}^{r} \left(z - e^{-\beta_i T} \right) \prod_{i=1}^{t} \left(z^2 - 2e^{-c_i T} \cos d_i T z + e^{-2c_i T} \right)}$$

where $k = r + 2t - 2n$, $k > 0$, and K_z is the normalization constant. For unity gain low-pass filters, K_z is determined by the requirement that $G(z)\big|_{z=+1} = 1$, and for unity gain high-pass filters, K_z is set by the requirement that $G(z)\big|_{z=-1} = 1$. This algorithm is similar to the matched z-transform algorithm of reference 4. The two algorithms give the same pole and zero locations except for the zeros at $z = -1$. In the use of the matched z-transform, it is common to add these zeros in an ad hoc manner for band-limited functions; thus, the two algorithms are identical in the way they are used.

As an example of the application of these algorithms, a first-order low-pass filter of the form $\frac{\beta}{s + \beta}$ would have the discrete transfer function

$$G(z) = \frac{K_z(z + 1)}{z - e^{-\beta T}}$$

where

$$K_z = \frac{1}{2}\left(1 - e^{-\beta T}\right)$$

The difference equation which would be programed on the digital computer would be

$$x_k = e^{-\beta T} x_{k-1} + \frac{1}{2}\left(1 - e^{-\beta T}\right)\left(u_k + u_{k-1}\right)$$

where u_k and x_k are the current values of the input and output of $G(z)$, and u_{k-1} and x_{k-1} are the values at the previous computation cycle.

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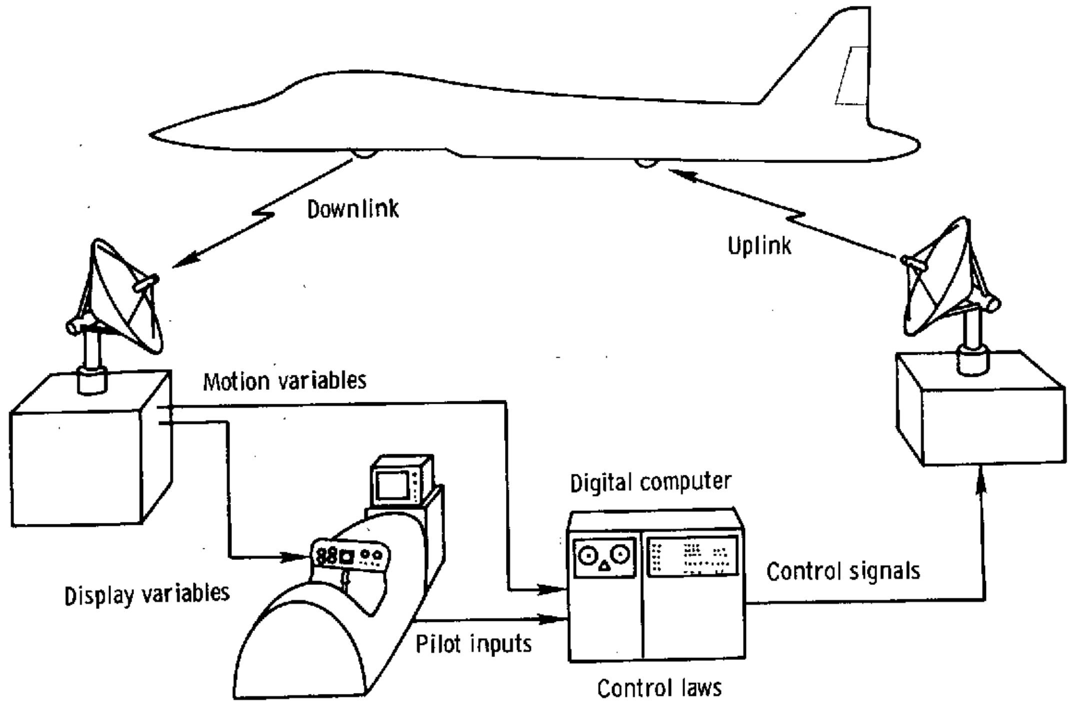


Figure 1. Remotely augmented vehicle concept.

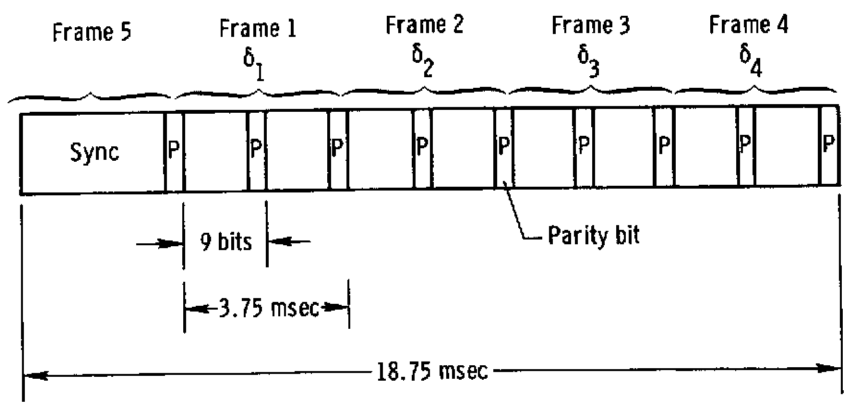


Figure 2. Telemetry uplink time schedule.

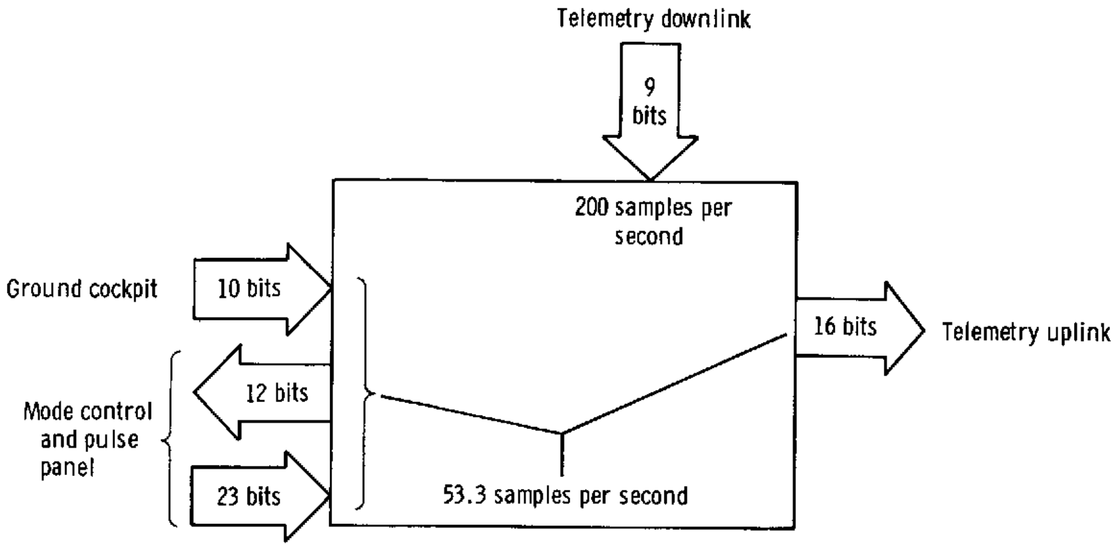


Figure 3. Interface at the digital computer.

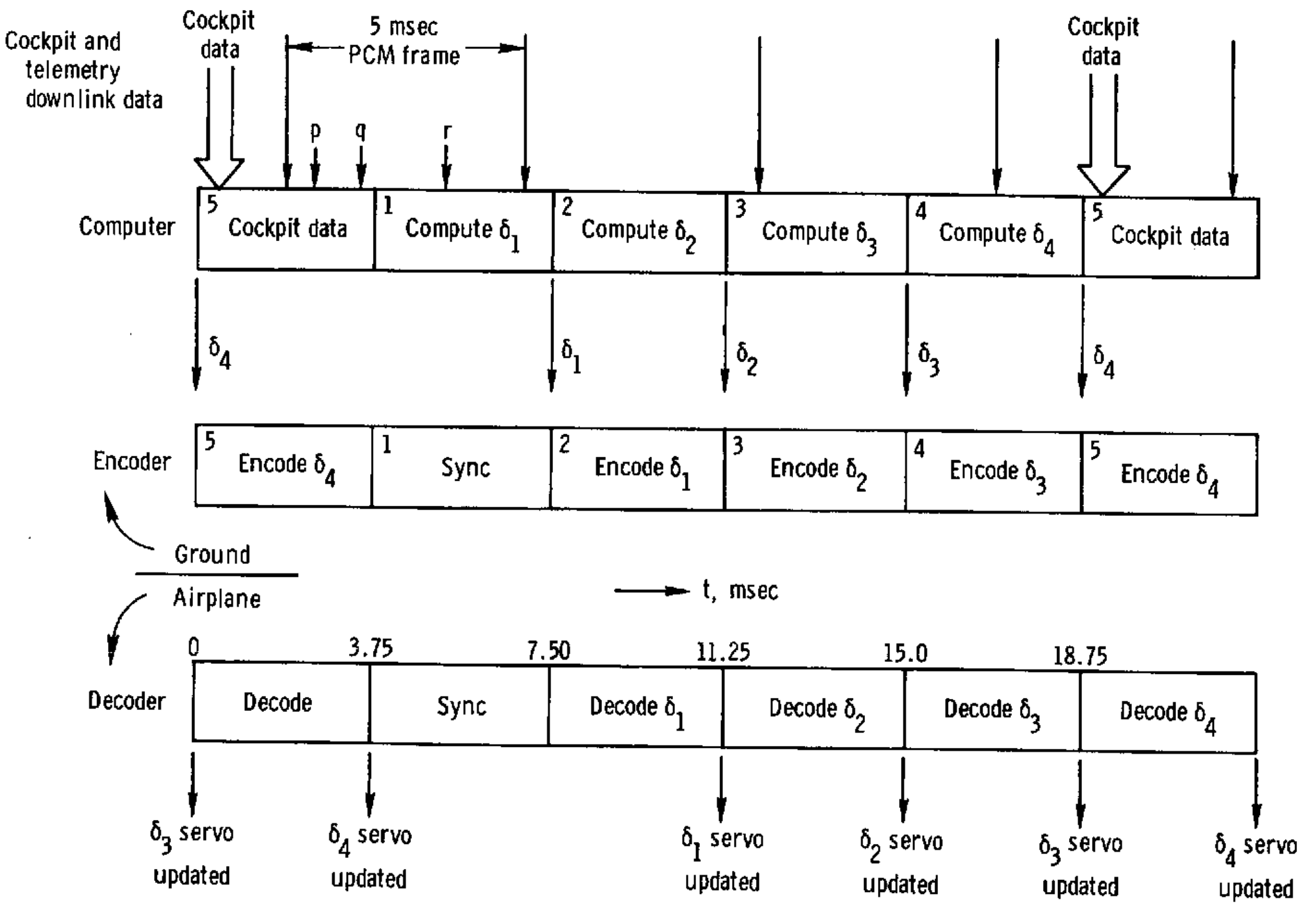


Figure 4. Computation sequence for RAV system.

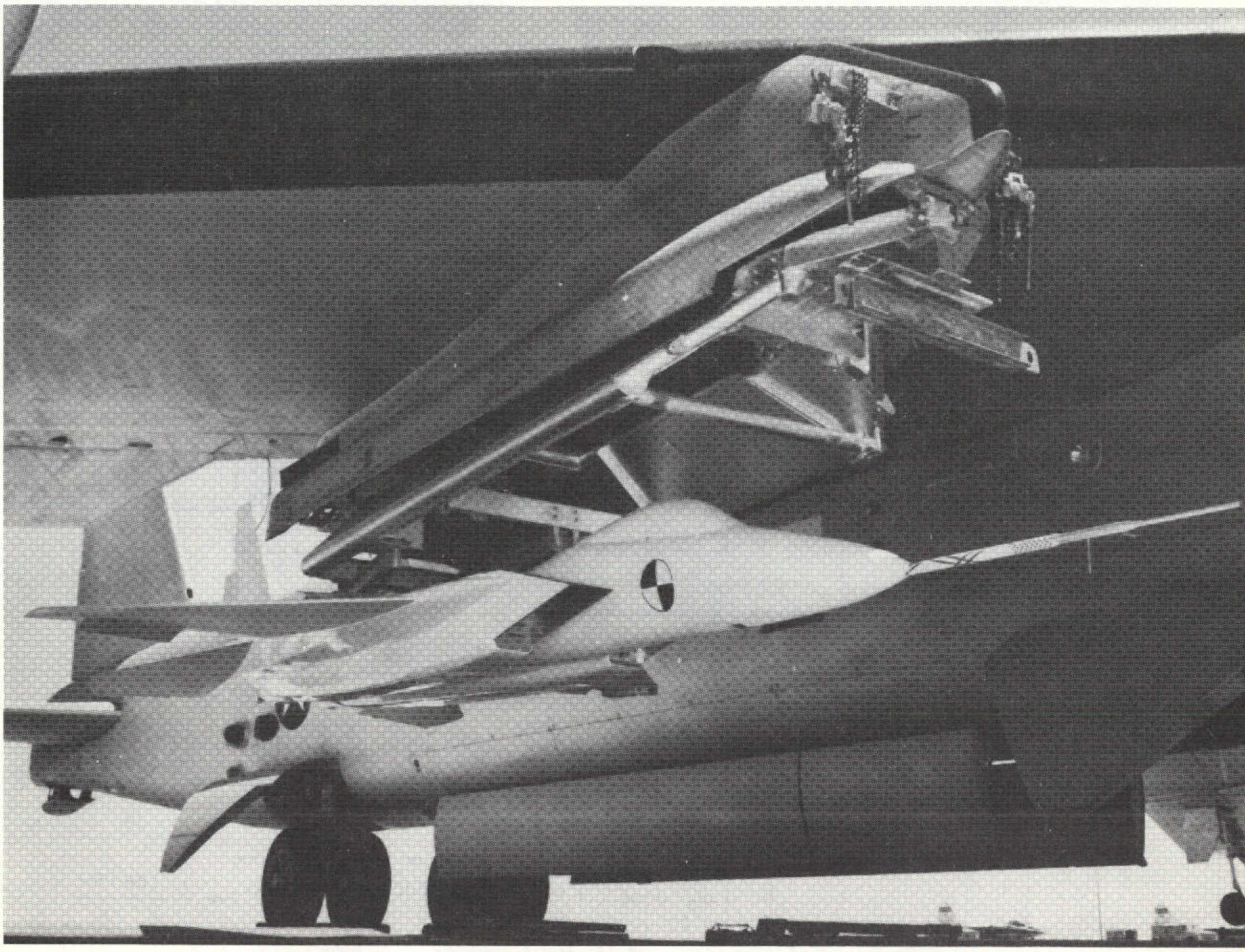


Figure 5. F-15 model in launch position on B-52.

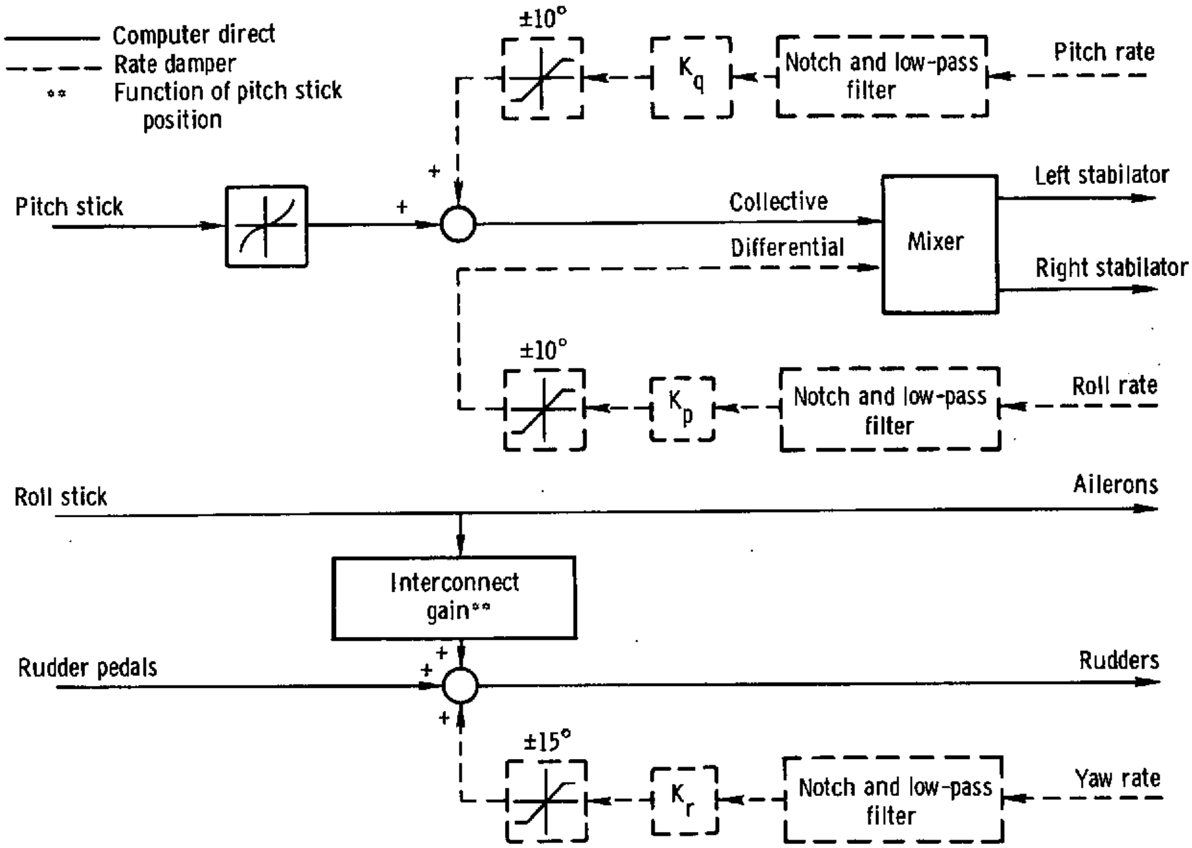
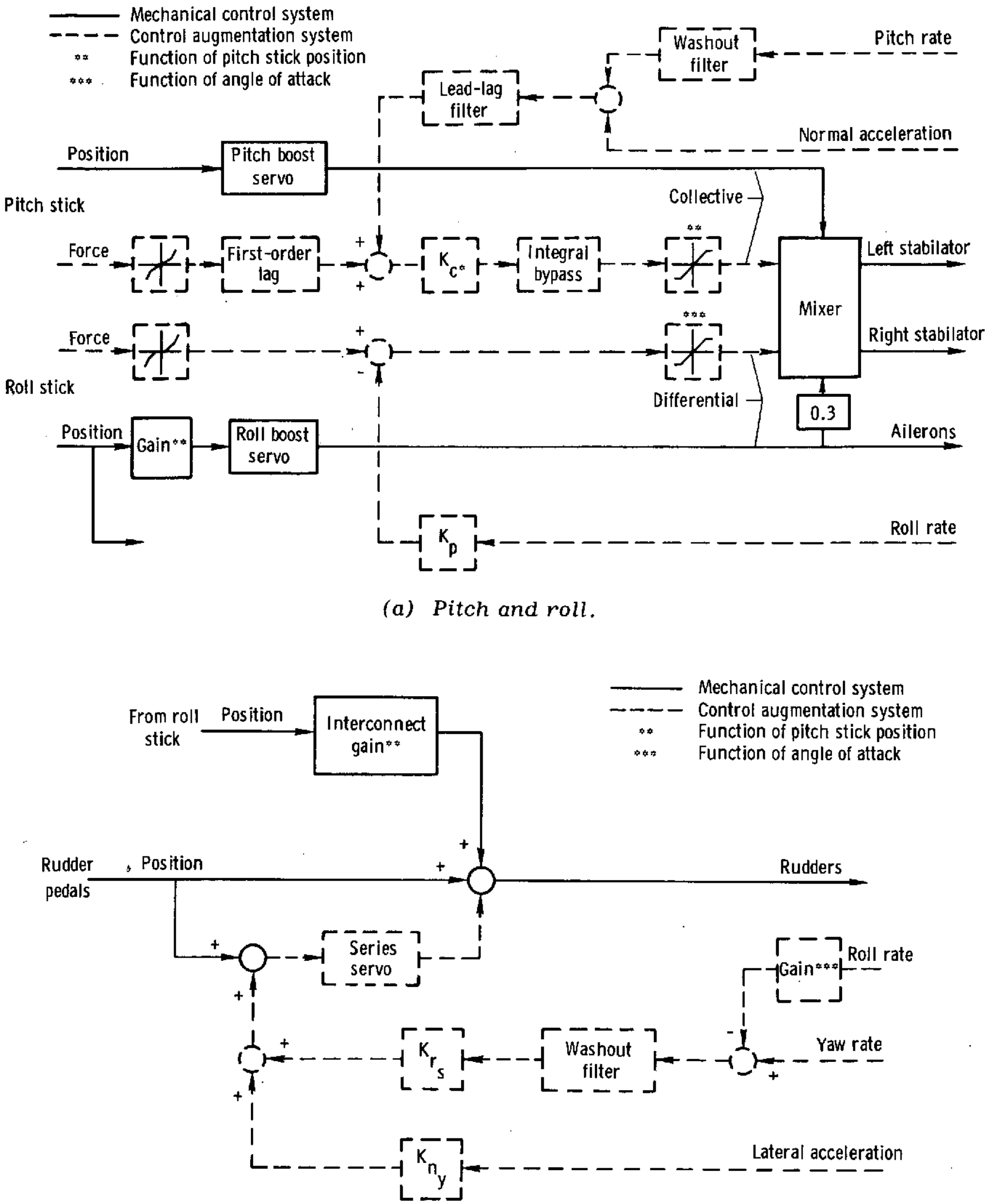


Figure 6. Block diagram of basic modes.



(a) Pitch and roll.

(b) Yaw.

Figure 7. Block diagram of simulated F-15 control systems.

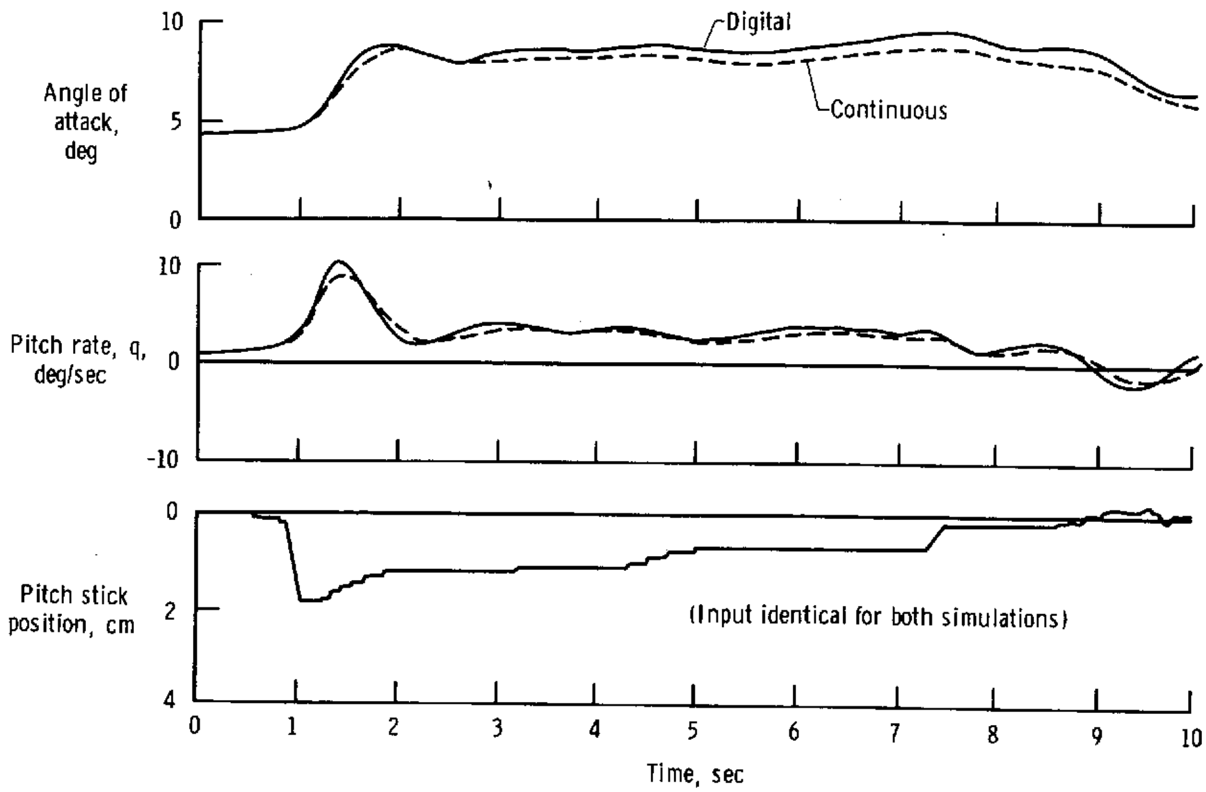


Figure 8. Comparison of digital RAV simulation and continuous RAV simulation. Pitch CAS mode.

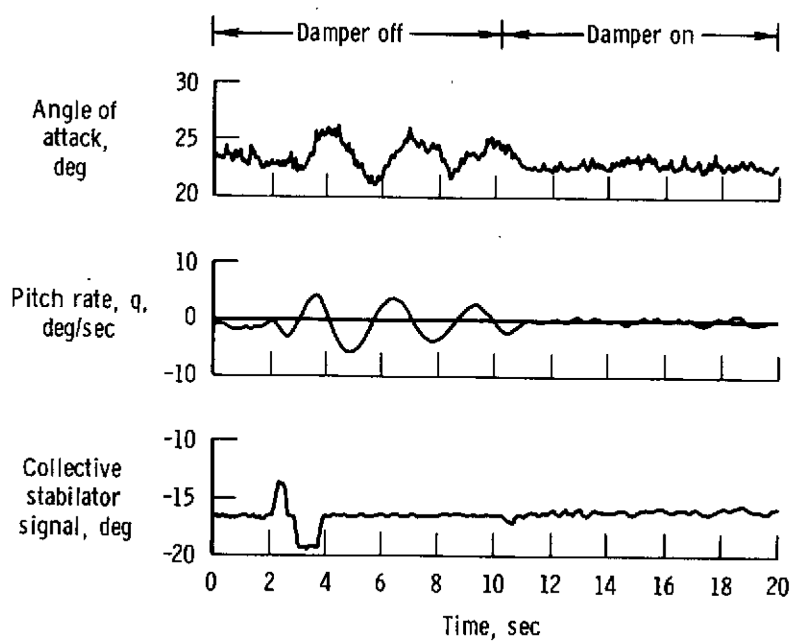


Figure 9. Pitch axis time response to stick doublet with dampers on and off.

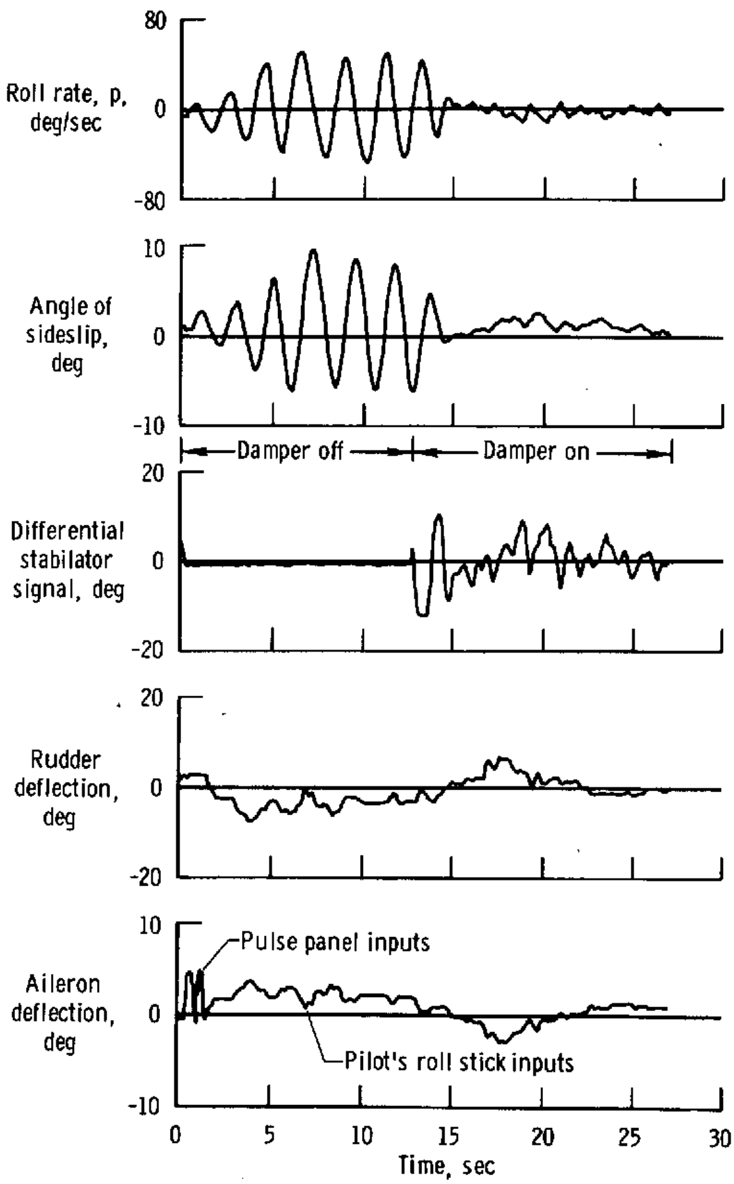


Figure 10. Lateral-directional time response to aileron input. Roll and yaw dampers on and off; angle of attack ≈ 30°.

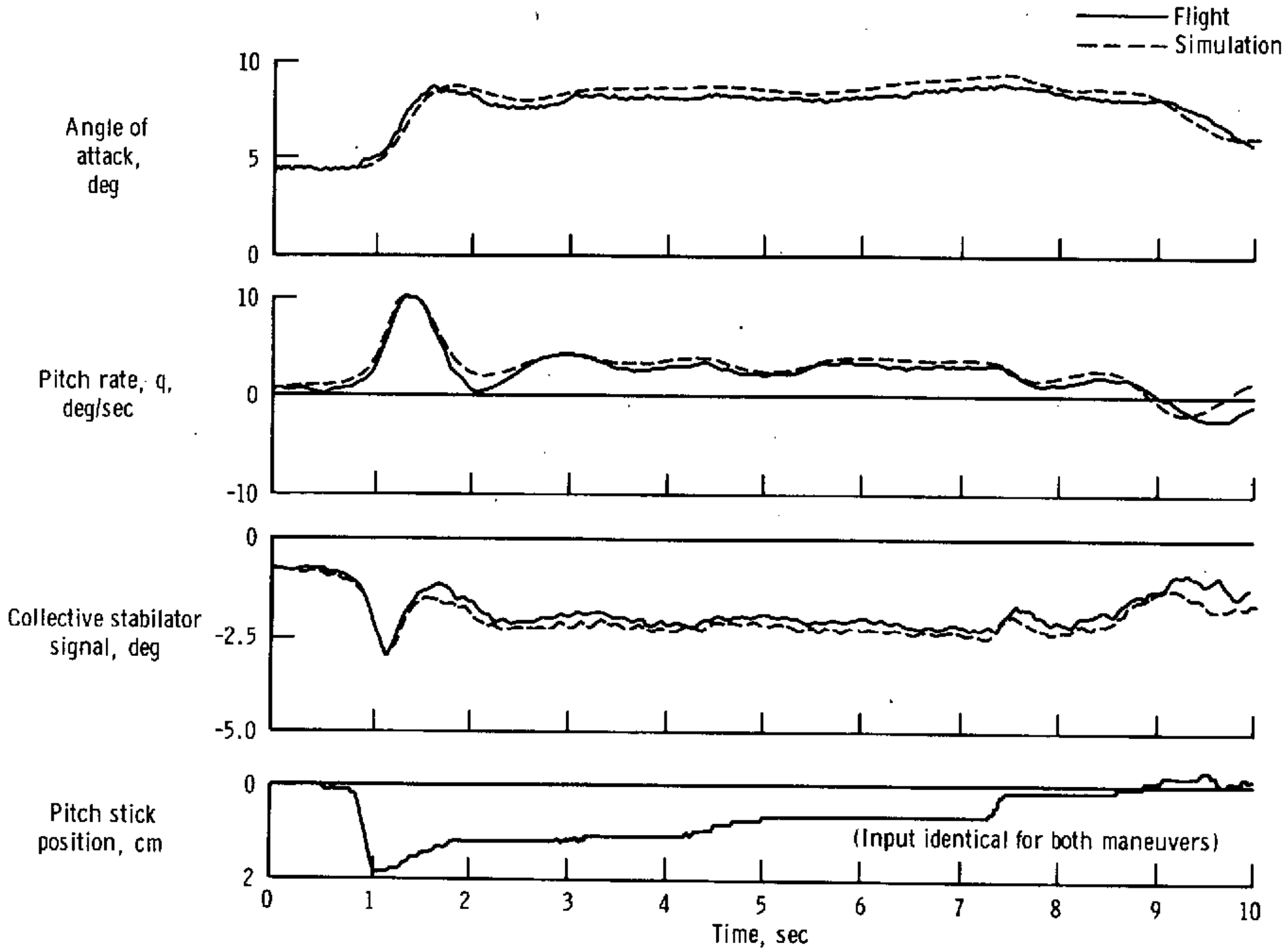


Figure 11. Comparison of flight-test and digital RAV simulation results for the pitch CAS mode.